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Policy change, land use, and agriculture: The case of soy production and cattle ranching in Brazil, 2001–2012

Florian Gollnow*, Tobia Lakes

Humboldt-Universität zu Berlin, Department of Geography, Unter den Linden 6, 10099 Berlin, Germany

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ABSTRACT

The Brazilian Amazon has experienced one of the world's highest deforestation rates in the last decades. Cattle ranching and soy expansion constitute the major drivers of deforestation, both through direct conversion and indirectly by land use displacement. However, deforestation rates decreased significantly after the implementation of the action plan to prevent and control deforestation in 2004. The aim of this study is to quantify the contribution of cattle and soy production with deforestation before and after the implementation of the action plan in the two states Mato Grosso and Pará along the BR-163. Specifically, we aim to empirically test for land use displacement processes from soy expansion in Mato Grosso to the deforestation frontier between 2001 and 2012. First, we calculated the relationships between deforestation rate and the change in cattle head and planted soy area respectively for the BR-163 region. Second, we estimated different panel regression models to test the association between processes of land use displacement. Our results indicate a close linkage between cattle ranching and deforestation along the BR-163 between 2001 and 2004. Soy expansion in Mato Grosso was significantly associated with deforestation during this period. However, these relations have diminished after the implementation of the action plan to control and prevent deforestation. With the decrease in deforestation rates in 2005, cattle ranching and deforestation were not directly linked, nor was soy expansion in Mato Grosso and deforestation at the forest frontier. Our analysis hence suggests that there was a close coupling of processes and spatial displacement until 2004 and a decoupling has taken place following the political interventions. These findings improve the understanding of land use displacement processes in Brazil and the methods offer potential for exploring similar processes in different regions of the world.

Introduction

The Brazilian Amazon has been subjected to one of the world's highest deforestation rates in the last decades (INPE, 2014b). Deforestation rates in the Legal Amazon increased from 2000 to 2004 from 18,226 km^2/year to 27,772 km^2/year respectively. Since then rates have been decreasing to 4571 km^2/year in 2012 (INPE, 2014b).

Understanding causes of deforestation and land use changes is crucial to curb deforestation. There are a large number of studies linking socio-economic and biophysical factors to deforestation in the Amazon region typically identifying drivers on municipal or grid level (Aguiar, Câmara, & Escada, 2007; Andersen & Reis, 1997; de Espindola, Aguiar, Pebesma, Câmara, & Fonseca, 2012; Laurance et al., 2002; Pfaff, 1999). Most commonly, a combination of proximate and underlying causes have been identified as the main drivers of deforestation, i.e., cattle farming, road building, and accessibility to markets and ports (Lambin & Geist, 2006; Margulis, 2004). These drivers describe the local circumstances influencing deforestation. However, underlying causes on regional and global level may influence local drivers and put pressure on land conversions (Meyfroidt, Lambin, Erb, & Hertel, 2013).

A couple of studies on regional and global drivers of deforestation in the Brazilian Amazon concentrate on the effects of global prices for agricultural goods, policy changes, and indirect land use change or land use displacement. Policy changes, especially the implementation of the action plan to prevent and control deforestation (PPCDAm, Plano de Ação para a Prevenção e o Controle do Desmatamento na Amazonia Legal) in 2004, had a significant effect on the decline of deforestation (Assunção, Gandour, & Rocha, 2012, 2013b; Hargrave & Kis-Katos, 2011). The PPCDAm focuses on three

* Corresponding author. Tel.: +49 30 2093 6893.
E-mail addresses: florian.gollnow@geo.hu-berlin.de, floriangollnow@hotmail.com (F. Gollnow), tobia.lakes@geo.hu-berlin.de (T. Lakes).

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areas: first, territorial management and land use, e.g., expansion of the protected areas network (PPCDAm I 2004–2007); second, command and control, e.g., improved monitoring, licensing and enforcement of environmental laws (PPCDAm II 2008–2011) and third promotion of sustainable practices, e.g., by credit policies (PPCDAm III 2012–2015) (MMA, 2013). Additional campaigns include the soy moratorium agreed on in 2006 and the cattle moratorium agreed on in 2009. Both have shown promise in changing the patterns of deforestation (Boucher, Roquemore, & Fitzhugh, 2013; Rosa, Souza, & Ewers, 2012; Rudorff et al., 2011).

Understanding processes of land use displacement or indirect land use change as an underlying driver of deforestation has gained special attention since the rapid expansion of export oriented agricultural production (Kim & Dale, 2011; Lapola et al., 2010; Meyfroidt et al., 2013; Searchinger et al., 2008). In Brazil, this discussion mainly focuses on the expansion of soybean and sugarcane production following the increased global and national demand for biofuel and animal fodder within the last decades (Andrade de Sá, Di Falco, Palmer, 2013; Morton et al., 2006). This expansion led to the hypothesis of indirect land use change, i.e., the displacement of cattle ranching to the Amazon rainforest where it drives deforestation (Andrade de Sá et al., 2013; Arima, Richards, Walker, & Caldas, 2011; Barona, Ramankutty, Hyman, & Coomes, 2010; Macedo et al., 2012; Nepstad, Stickler, & Almeida, 2006; Richards, 2012).

Most studies on displacement processes in Brazil focus on the recent expansion of soy area, particularly on Mato Grosso (MT) as one of the world's most important production areas (DeFries, Herold, Verchot, Macedo, & Shimabukuro, 2013). Morton et al. (2006) showed that soybean expansion most often replaced pasturelands. This conversion can be argued to be a process of intensification, since financial returns per area of land increased (Brandão, Castro de Rezende, Da Costa Marques, 2005). However, if the output of the replaced activity faces a relatively inelastic demand, as it is likely for stable food products like meat, the production will probably be reconstituted in another place where it can act as a local driver of land use change (Andrade de Sá, Palmer, Engel, 2012; Andrade de Sá et al., 2013).

In detail, Nepstad et al. (2006) suspected that the expansion of the Brazilian soybean industry drove cattle expansion of the Amazonian cattle herd indirectly. Barona et al. (2010) concluded that the expansion of soy production might have operated as an underlying driver of deforestation displacing pasture further north into the forested areas, where pasture expansion is the predominant proximate cause of deforestation. Using a panel regression approach Arima et al. (2011) and Richards (2012) found soy expansion in Brazil had a significant effect on deforestation in the Amazon forest between 2002 and 2008. However, analyzing the migration history of farmers and ranchers, Richards (2012) could not clearly identify patterns of movement to support the idea of "spatial redistribution of knowledge and capital" from the soy expansion areas to the forest frontier.

This study aims to understand the coupling of cattle production and soy production with deforestation processes within the Amazon region along the BR-163. The BR-163 region has been one of the most dynamic forest frontier regions within the Brazilian Amazon connecting the soy production areas in Mato Grosso (MT) with the forested region in the north of MT and Pará (PA). We analyzed the local evolution of cattle and soy production in relation to deforestation, and the effect of distant soy expansion in Mato Grosso on deforestation at the forest frontier using a fixed effects panel regression. Different from earlier studies, we explicitly focus on the change in displacement processes before and after the implementation of the PPCDAm and aim for statistical evidence for displacement processes.

More specifically our research questions are:

- How does the coupling of land use processes, i.e., cattle and soy production with deforestation, change along the BR-163 between 2001 and 2012?
- Can we find statistical evidence of land use displacement from the soy expansion area in Mato Grosso as source region to the forest frontier areas in the Brazilian Amazon? How does land use displacement change following the implementations of the PPCDAm in 2004?

Material and methods

Study region

This study explores one of the hotspots of deforestation in the Brazilian Amazon: the region along the BR-163 traversing the Brazilian Amazon from Cuiaba, MT to Santarem, PA (INPE, 2014b). We selected those 31 municipalities that intersect with a 150 km buffer along the road starting in the south with the Amazon Biome border and framed in the north with the Transamazonica road (Fig. 1). This area captures the most relevant frontier development following the construction of the highway in 1973 as an export corridor for agricultural productions in MT (Coy & Klingler, 2011; Fearnside, 2007).

The study region comprises 500,580 km^2 and is dominated by forest area (2001: 411,249 km^2, 2012: 376,622 km^2), cattle ranching (2001: 4,245,462 heads, 2012: 7,436,330 heads), with an estimated stocking density of 0.009 animal per km^2 in 2006 and 0.01 animal per km^2 in 2013 (Geraldo, Alves, & Contini, 2012; Walker, Patel, & Kalif, 2013), and soybean production (2001: 3430 km^2, 2012: 14,884 km^2). Other livestock only constitute a minor share of total livestock population (see Appendix Fig. A2). Soybeans as the main crop are increasingly planted in double cropping systems followed by maize, cotton or a non-commercial crop (Arvor, Jonathan, Meirelles, Dubreuil, Durieux, 2011a; Arvor, Margareth, Dubreuil, Bégué, & Shimabukuro, 2011). Deforestation rates increased sharply between 2001 and 2004 from 3995 km^2 to 6431 km^2 and decreased until 2012 to 728 km^2 (INPE, 2014b).

Following the implementation of the PPCDAm in 2004, a number of protected areas, indigenous lands and sustainable use areas were expanded or created within the study region (Fig. 1). Additionally, command and control policies were enforced, e.g., the opening of an IBAMA (Brazil's federal environment protection agency) office in Novo Progresso in 2007, the identification of priority areas for law enforcement, and a rapid response program based on the 15 days DETER (Detecção de Desmatamento em Tempo Real) monitoring interval (Anderson, Shimabukuro, DeFries, & Morton, 2005; Assunção, Gandour, & Rocha, 2013a; INPE, 2014a). In 2008, changes in public credit policies were implemented conditioning the concession of rural credit upon compliance with legal and environmental regulations. This included, among others, legal property rights (Cadastro Ambiental Rural) and limited deforestation per municipality (Governo do Pará). These regulations especially affected those municipalities where cattle ranching is the predominant activity (Assunção et al., 2013b). Additionally, in 2006 the "soy moratorium" and in 2009 the "beef moratorium" were implemented. Both are agroindustry led initiatives with the objective to limit deforestation by direct encroachment of soy fields and pasture areas into forest (Boucher et al., 2011; Rudorff et al., 2011).

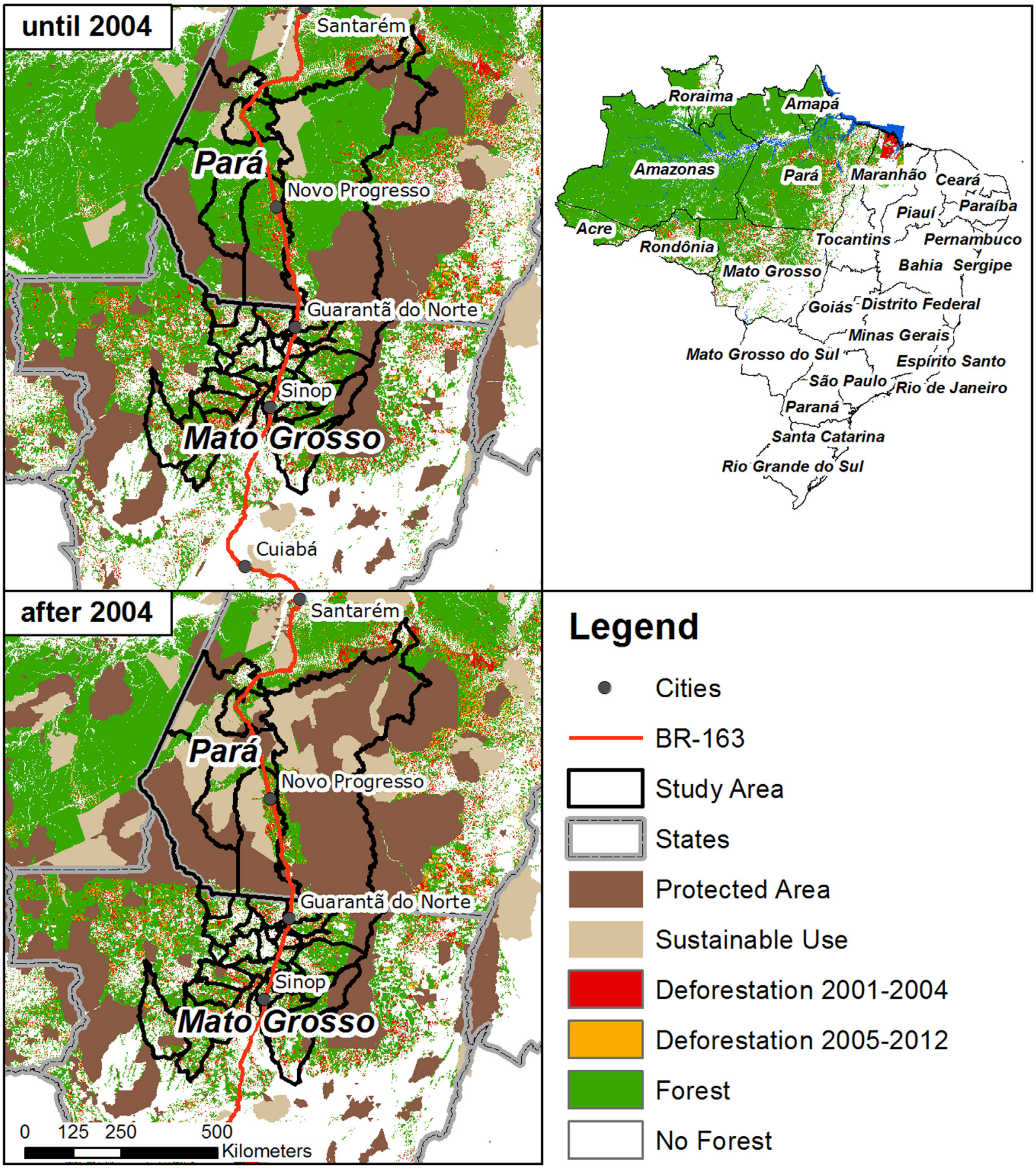

Fig. 1. Study region.

Data

Data on annual deforestation rates (km^2) aggregated per municipality was acquired from PRODES/INPE for the years 2001–2012 (Instituto Nacional de Pesquisas Espaciais INPE, 2014b). Since 1988, INPE has been monitoring and improving their methodology to accurately map deforestation (Câmara, Valeriano, & Soares, 2006; INPE, 2014b). PRODES deforestation estimates refer to the first of August of each year and account for gross deforestation with a minimum mapping unit of 6.25 ha (Câmara et al., 2006). To assess cattle farming and soy production we used annual data on planted soy area in km^2 and annual heads of cattle per municipality in 1000. Annual pasture area is – to the knowledge of the authors – unfortunately not available for 2001 to 2012. Both datasets were acquired from the municipal livestock and agricultural production survey available in the SIDRA-Database which provides one of the most detailed public available databases for Brazil on an annual basis (IBGE). Crop area estimates from the agricultural survey are counted separately for each crop rotation (Morton et al., 2006). The annual planted soy area describes the area demand of soy production independent of production increases or land use intensification based on increasing double cropping practices. From these datasets, we calculated the annual changes of cattle head and planted soy area (km^2) per municipality.

Methods

First, we analyzed the relationship between the two main land uses, i.e., cattle and soy production change with deforestation rate, using deforestation transfer ratios. Second, we used fixed effects models to estimate the effect of distant soy expansion and local cattle expansion on deforestation (2.3.1). Model specification was built upon a selection of source and target municipalities of possible land use displacement. We used separate models to evaluate how land use displacement processes changed following the implementation of the PPCDAm by comparing the period before the implementation (2001–2004) and afterwards (2008–2012) (2.3.2).

Coupling between deforestation, cattle and soy production

To analyze the linkages and dynamics of soy and cattle production in relation to deforestation processes we calculated an annual deforestation transfer ratio for the whole study region (Gasparri, Grau, & Gutiérrez Angonese, 2013).

$$\text{Deforestation Transfer Ratio}_t = \frac{\sum_{i=1}^{n} \text{Deforestation Rate}_{it}}{\sum_{i=1}^{n} \text{Land Use Change}_{it}} \tag{1}$$

This deforestation transfer ratio quantifies the relationship between the summed deforestation rate (km^2) over the municipalities i at year t and the respective land use change, i.e., summed change of cattle (1000 heads) and summed change of planted soy area (km^2) over i at year t. To account for the full time periods before and after the implementation of the PPCDAm we explicitly compared how the deforestation ratio changed between 2001 to 2004 and 2005 to 2012.

A deforestation transfer ratio of one, means that an area of one km^2 was deforested for 1000 additional cattle head. For planted soy area change a value of one refers to one km^2 deforested area for one additional km^2 of soy area planted. Small values imply a decoupling of the two processes, for instance, land use increases, but deforestation rates do not equally respond to it. An intensification of cattle production (increase of stocking density) results in a decrease in the deforestation transfer ratio, because the decrease in area required for production reduces the need to clear new land by deforestation. In the case of soy area change, values around a one to one relation (1 km^2 to 1 km^2) generally imply a coupled system where changes in land use are mirrored in changes in deforestation rates. Equally for cattle (change in 1000 heads), a 10 to one ratio, considering an estimated stocking density of about 0.01 animals per km^2, generally implies a coupled system. Larger values of the deforestation transfer ration reflect an increase of deforestation without similar changes in the land use at hand. This suggests a minor direct contribution of the respective land use on deforestation.

Panel regression model

For the statistical analysis of land use displacement following soy expansion in MT and cattle ranching expansion at the forest frontier, we estimated fixed effects panel regressions. The model specification of land use displacement was built upon the definition of annual target and source municipalities. The target municipalities describe those municipalities within our study region along the BR-163 in MT and PA where cattle population increased from one year to the other. From those target municipalities, we only included the ones where soy expansion was smaller than deforestation so as to omit municipalities where soy expansion drove deforestation directly. A minimum of 30% forest cover was set as a threshold to reduce the effect of decreasing likelihood of deforestation as forest cover declines (Richards, 2012). The source region encompasses all municipalities in MT, which experienced soy expansion and are not defined as target municipalities. This reduced the analysis to those municipalities from where displacement of cattle could possibly take place because of soy expansion. It accounts for the spatial and temporal heterogeneity of potential land use displacement within the study region.

Deforestation rate in the target region was set as the response variable and total soy expansion in the source region as the explanatory variable. To account for the difference in size of the target municipalities in relation to soy expansion we introduced a weight matrix, defined as municipality area divided by the maximum municipality size, assuming that the amount of displacement is related to the municipality size. We also examined if changes in cattle population in the target regions correlated with deforestation to test the assumption that soy expansion displaced cattle and thereby induced deforestation.

The general fixed effects panel model is defined as:

$$y_{it} = \alpha_i + \beta' X_{it} + u_{it} \tag{2}$$

With y_{it} the response variable at municipality i and time t, α_i the individual intercept for each municipality, β the slope of the estimation, X_{it} the explanatory variable at time t in municipality i, respectively weighted by the municipality area and u_{it} the error component. The fixed effects model accounts for time constant unobserved heterogeneity between the municipalities, such as soil suitability and differences in relief, which structurally favor one municipality over another (Arima et al., 2011; Croissant, Millo, & others, 2008). The analysis was done with the plm-package in R (Croissant et al., 2008; R Core Team, 2013).

To minimize the effect of the decrease in soy prices between 2005 and 2007 (Appendix Fig. A1) and to avoid the transition period following the implementation of the PPCDAm I to PPCDAm II, we designed the models for the years 2001–2004 and 2008 to 2012. Moreover, we focused on the separate association between deforestation rates and soy and cattle changes respectively. Thereby, we avoid problems of collinearity between the datasets in the model and are able to interpret the model results focused on the specific association. In total we calculated four models: A1 (2001–2004): Deforestation = *f*(Weights*Soy Expansion), B1 (2001–2004): Deforestation = *f*(Cattle Expansion), A2 (2008–2012): Deforestation = *f*(Weights*Soy Expansion) and B2 (2008–2012): Deforestation = *f*(Cattle Expansion).

To obtain a more robust panel dataset, those municipalities with less than three observations were eventually omitted from the analysis. For the first period of four years, 21 target districts were identified with 3–4 observations over time; for the second period of 5 years, 13 target districts were identified with 3–5 observations over time. Finally, model fit was quantified by calculating the R^2 value.

In line with earlier studies (Andrade de Sá et al., 2013; Arima et al., 2011; Richards, 2012), we ran our models including a one year lag of soy expansion in the source region. The lagged model led to similar overall results but did not improve the explanation of land use displacement before the implementation of the PPCDAm (measure by R^2). For the period after the implementation of the PPCDAm, both coefficients (lagged and non-lagged soy expansion) were negative and significant which underpins the results from the non-lagged model (Appendix Table A1).

Results

Coupling between deforestation, cattle and soy production

We identified distinct changes in the processes of deforestation, soy and cattle production in the entire study region between 2001 and 2012.

Cattle population increased from 4.245 million heads in 2001 to 6.2 million heads in 2006, followed by a short decline to 5.67 million in 2007 (Fig. 2). Cattle population rapidly expanded again in 2008 surpassing the number of cattle present in 2006 (6.24 million heads) and increased to 7.53 million in 2011 before it declined slightly in 2012 (7.44 million heads). Soy area increased rapidly within the study region from 3430 km^2 in 2001 to 10,365 km^2 in 2005. Similar to cattle, soy showed a short decline in area in 2007 to 8082 km^2 but then strongly increased again to 14,884 km^2 in 2012.

Between 2001 and 2004 the transfer ratio varied along a value of about 10 for deforestation rate and cattle change, which refers to an area of 10 km^2 deforestation for each additional 1000 cattle per year (Fig. 3a). For 2005 and 2006 we received high values that show that more deforestation per increase of cattle occurred than before. Especially in 2006, the deforestation rate was largely independent from changes in the number of cattle. In 2007 we observed a negative transfer ratio, following the decline in the number of cattle within the study region, accompanied by dropping deforestation rates. The transfer ratio stabilized for the following 4 years at a value of about two. This refers to a deforestation area of about two km^2 for each additional 1000 cattle. Associated with the decline in cattle population in 2012, the transfer ratio again showed negative values. The comparison between the aggregated period of 2001–2004 and 2005 to 2012 indicated a slight decline from 9.98 to 9.21.

The transfer ratio between deforestation rate and planted soy area change was far above a one to one relationship for the years 2001–2005 (Fig. 3b). Up to five times as much deforestation as soy expansion occurred. Planted soy area declined for the years 2006, 2007, and 2009. In 2008 and 2010 the transfer ratio of soy expansion stayed just below one and declined in the following years to 0.42. The aggregated transfer ratio declined from 3.40 (2001–2004) to 2.34 (2005–2012) showing that less area was deforested in relation to new soy area.

Panel regression model

Using the panel regression models, we estimated the displacement effects of soy expansion in MT on deforestation along the BR-163. To specifically focus on the process of displacement following soy expansion in MT displacing cattle production to the forest frontier, we defined a target region of cattle expansion in the study region and a source region where planted soy area expands in MT. The target municipalities point to the spatial-temporal development of the deforestation frontier where cattle expanded (Fig. 4). While cattle expansion was dominant for most of the study region in the first 5 years, cattle ranching eventually lost some of its importance in the south of the BR-163 region. From the 31 municipalities a maximum of 20 in 2001 and a minimum of 6 in 2012 were selected as target municipalities.

The number of source municipalities, i.e., from where displacement could possibly occur, steadily increased from 44 to 81 municipalities between 2001 and 2004 (Fig. 4). In 2008, 64 municipalities were identified as source region of possible displacement. In the following years, soy area again expanded in the other municipalities. In 2012, 72 municipalities in MT were defined as source region.

For these two periods, we evaluated the weighted summed soy expansion in the source region as explanatory variable for deforestation in the target municipalities (Table 1: A1, A2). In the following, we tested whether cattle expansion in the target region was a significant explanatory variable for deforestation (Table 1: B1, B2), to verify the indirect link of soy expansion in MT and deforestation along the BR-163.

Model A1 and B1 describe the association for the pre-PPCDAm period from 2001 to 2004 (Table 1). We identified a significant association between soy expansion in the source region and deforestation in the target municipalities (Table 1: A1). Similarly, the increase of cattle was significantly associated with deforestation in the target municipalities for the first period (Tab.1: B1). Both models show a low but significant R^2 of 0.08 and 0.07 respectively.

Model A2 and B2 describe the period between 2008 and 2012 following the implementation of the PPCDAm. Soy expansion returns a significant negative beta (Table 1: A2), while cattle change in the target municipalities continues to be significant and positively associated with deforestation (Table 1: B2). However, the effect of cattle ranching decreased by almost 50% compared to the period 2001 to 2004, while the R^2 of the model increased threefold.

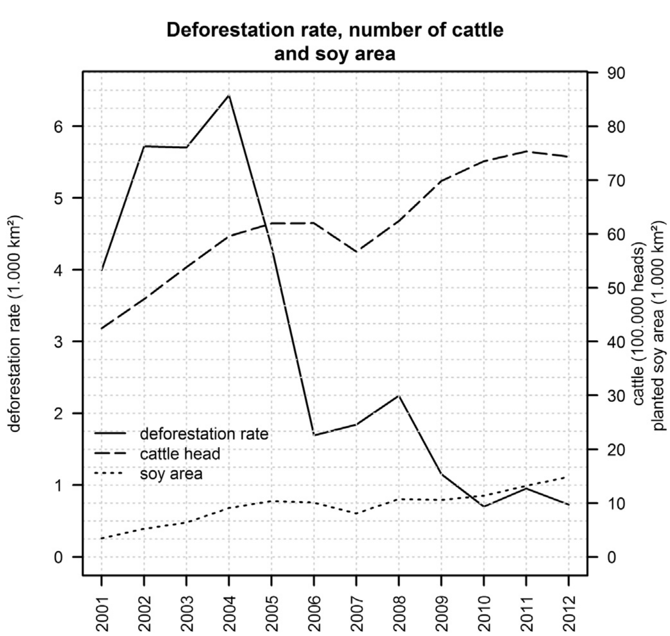

Fig. 2. Deforestation rate, number of cattle, and planted soy area.

Discussion

Our findings suggest important changes in the linkages between the three land use processes, soy expansion, cattle dynamics and deforestation along the BR-163 between 2001 and 2012.

The year of implementation of the PPCDAm was associated with a structural break in terms of land use. Before this, cattle changes were closely coupled with deforestation along the BR-163. This is indicated by a transfer ratio of about 10, which approximates the pasture area requirements considering the estimated stocking density for the Amazon of 0.009 animals per km^2 in 2006 and 0.01 animal per km^2 in 2013 (Geraldo et al., 2012; Walker et al., 2013). Cattle changes were therefore directly reflected in the amount of deforestation during the respective year. We hence assume that cattle increases were related to the expansion of pastures, rather than to the intensification of production system, i.e., an increase in stocking density, which would require less land. This is in line with earlier studies, which identified the BR-163 frontier region as an area of extensive cattle production (Bowman et al., 2012).

The years 2005 and 2006 were characterized by an increase of the deforestation transfer ratio. This divergence of deforestation rates and cattle change possibly indicates a process of structural inertia of the local adaptation to the new regulations (Hannan & Freeman, 1984). While the number of cattle declined in 2007,

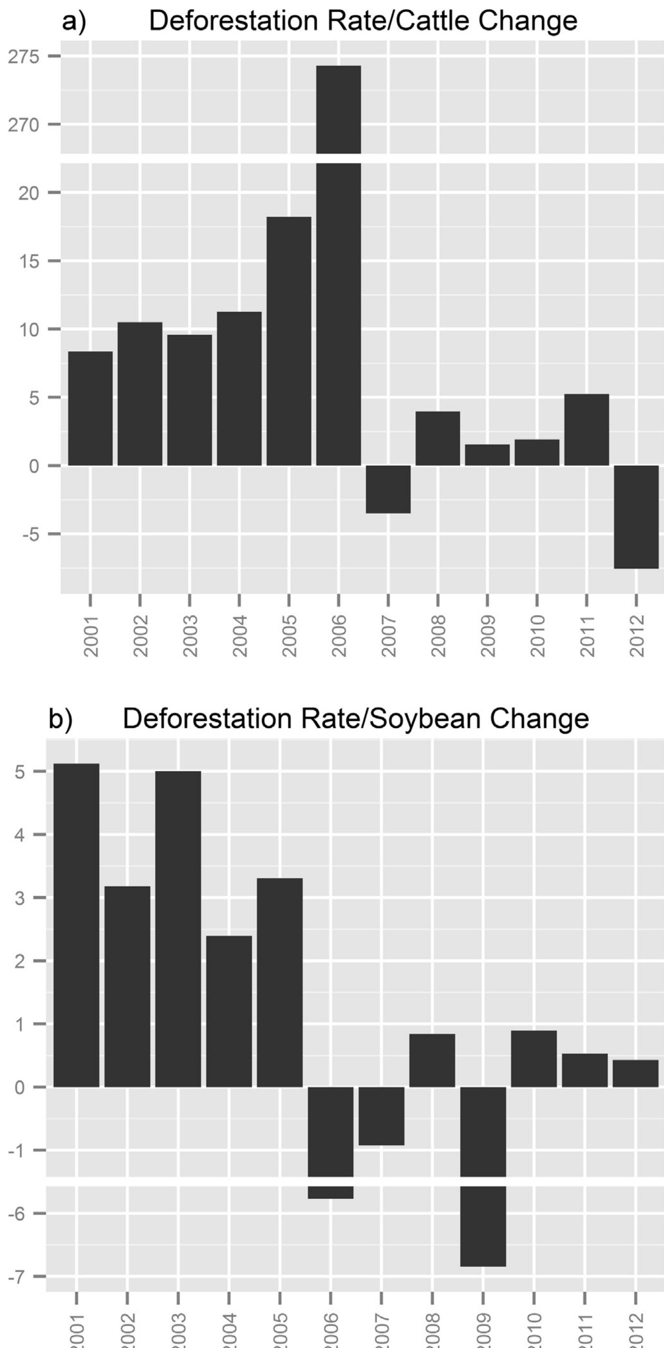

Fig. 3. a) Transfer ratio of changes in cattle (in 1000 heads) and deforestation rate (in km^2), b) Transfer ratio of soy area change (in km^2) and deforestation rate (in km^2).

deforestation continued on a low level. This resulted in a surplus of cleared area, despite the decrease in deforestation rate.

Since 2008, the change in cattle population and deforestation appeared temporally decoupled. Cattle population increased, already surpassing the number of cattle in 2004 by 2008, but deforestation rates did not respond with a similar increase (Fig. 3a). From 2008 onwards, the transfer ratio of deforestation rate and cattle change stayed far below the ratio of the pre-PPCDAM period. Increased land constraints following the implementation of PPCDAm likely fostered a process of intensification of ranching activities on already cleared lands as observed in other regions of Brazil (Strassburg et al., 2014). This supports the finding of Assunção et al. (2012) who argues that if policy measures had not been implemented deforestation rates would have increased after the recovery of agricultural prices in 2007. However, the transfer ratios aggregated for the pre-PPCDAm period (2001–2004) and post-PPCDAm period (2005–2012) decreased only slightly. This indicates that the decoupling of cattle population and deforestation since 2008 can partly be attributed to deforested areas in 2006 and 2007. Those deforested areas in 2006 and 2007 likely provided pasture areas for the expansion of cattle ranching between 2008 and 2012.

As expected, soy expansion within the BR-163 region was not as closely linked to deforestation increases for the early 2000s. Deforestation rates by far exceeded the increase of soybean production in the area.

The decline in soy area in 2006 and 2007 was quickly regained in 2008, whereas we found a roughly stable amount of area used for soy production from 2008 to 2009. In 2008 and 2010, soy expansion stayed below the one to one ratio, which indicates an increased pressure on land due to the expansion of soy plantations within the BR-163 region because the expansion rate was larger than the deforestation rate.

Following the soy moratorium in 2006, most soy expansion was found to occur on already cleared lands (Macedo et al., 2012). Therefore, soy expansion can rather be viewed as an indirect driver of deforestation, expanding on pasture areas instead of encroaching into primary forest itself. The soy moratorium additionally inhibited large scale soy expansion to areas cleared after 2006 (Rudorff et al., 2011, 2012). However, the change in the public credit policy following the implementation of the PPCDAm might also have modified farmers' decision to change from cattle to soy production. Credits for soy production are not as dependent on the official rural credit system, where most of the financial requirements are meet by the processing industry (Assunção et al., 2013b). Yet, during the decline of soy area in 2006, 2007, and 2009, and the decline in cattle heads in 2007 deforestation continued. This resulted in an addition of cleared areas, partly providing land for the later expansion. When comparing the aggregated transfer ratios for the period 2001to 2004 and 2005 to 2012, the ratio declined from 3.40 to 2.34 km^2 area cleared for each km^2 of soy expansion.

Concerning the first research question, we can summarize that deforestation was closely coupled to cattle ranching until 2004. In 2005 to 2007 more area was deforested than actually needed in

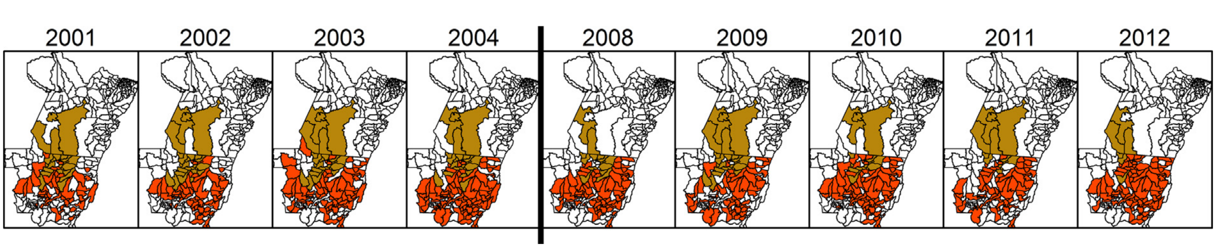

Fig. 4. Municipalities identified as target region (in brown) and source region (in red) from 2001 to 2012.

Table 1
Fixed effects panel regression.

Model	Time period	Model specification	β	R^2
A1	2002–2004	Deforestation $\text{Rate}_{it} = f(W_i \sum_{i=1}^{n} \text{Soy expansion Source}_{it})$	0.05621*	0.088
B1	2002–2004	Deforestation $\text{Rate}_{it} = f(\text{Cattle change in } 1,000 \text{ Target}_{it})$	0.88441*	0.077
A2	2008–2012	Deforestation $\text{Rate}_{it} = f(W_i \sum_{i=1}^{n} \text{Soy expansion Source}_{it})$	−0.05689.	0.098
B2	2008–2012	Deforestation $\text{Rate}_{it} = f(\text{Cattle change in } 1,000 \text{ Target}_{it})$	0.49755**	0.256

Model A1 & B1: Unbalanced Panel: $n = 21$, $T = 3–4$, $N = 74$.
Model A2 & B2: Unbalanced Panel: $n = 13$, $T = 3–5$, $N = 47$.
Significance levels: $p < 0.1$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

respect to changes in cattle population and soy production of the previous years. 2008 to 2012 can be interpreted as a temporal decoupling of cattle and soy production from deforestation. This can be understood as a combination of intensification processes and expansion on areas cleared in the previous years. Additionally, soy production gained importance in the region along the BR-163 compared to the early 2000s.

Moreover, our findings allow an empirical assessment of the land use displacement processes in the region. The definition of a target region explicitly considers the spatio-temporal heterogeneity of the study region taking into account the decrease of cattle production for some of the municipalities. The selection spatially describes the development of the cattle-deforestation system. In the south of the study area, cattle lost some of its importance during the period of analysis. Additionally in 2007, 2008, 2010, and 2012, some municipalities in PA dropped out of the frontier definition. Soy expansion in MT outside the target region expanded constantly until 2005, followed by a decrease of source municipalities until 2008. The decrease of municipalities selected as source municipalities follows the decline of the soybean prices (Appendix Fig. A1). In 2007, maize was partly used as a substitute for soybean (Reenberg & Fenger, 2011, see Fig. A3). This suggests that the following expansion was not as likely to displace cattle but to replace maize planted during the period of low prices.

Based on the selected municipalities of target and source regions our results of the fixed effects regression supported the hypotheses of indirect land use change for the pre-PPCDAm period. Methodologically, we deviated from a distance-weighted influence of the source region to the target municipalities as proposed by Arima et al. (2011) and Richards (2012). Firstly, because our study focuses on regional displacement effects, and secondly because we would have difficulties arguing that within the displacement discourse the influence of a close place is higher than from a distant location.

The fixed effects regression indicated that soy expansion in the source municipalities had a significant effect on deforestation on the selected target municipalities for the 2001 to 2004 period. To underpin the indirect link between soy expansion and deforestation, we confirmed that cattle ranching in the target municipalities had a significant correlation with deforestation. This result supports data driven evidence for earlier hypotheses of land use displacement (Barona et al., 2010; Nepstad et al., 2006) and is in accordance with findings from Arima et al. (2011) and Richards (2012) who found soy expansion in the fringes of the Brazilian Amazon a driver of deforestation for the years 2001–2008. Different to the studies of Arima et al. (2011) and Richards (2012), we partitioned our analysis before and after the implementation of the PPCDAm. The indirect link between soy expansion in MT with deforestation in the target municipalities could not be confirmed for the post-PPCDAm period 2008 to 2012. The effect of cattle ranching on deforestation decreased by almost 50% and the model fit (R^2) increased to 0.26. This is in accordance with our earlier findings of cattle ranching decoupling from deforestation for the years 2008–2012. Most importantly, soy expansion in the source municipalities decoupled from the deforestation dynamics in the target municipalities for the 2008 to 2012 period. This means that land use displacement due to soybean expansion leading to deforestation cannot be understood as a continuous process since the beginning of the rapid expansion of soy production in MT.

To summarize, regarding the second research question, we found statistical evidence of land use displacement of soy expansion being associated with deforestation for the pre-PPCDAm period. Processes changed after the implementation of the PPCDAm. Soy expansion and deforestation were not significantly associated, while the impact of cattle ranching on deforestation declined.

Results are challenged by a number of limitations referring to the data quality, spatial extent, the temporal resolution, and model specification. We fully relied on the quality of PRODES/INPE deforestation estimates and IBGE annual survey data, which are the best available data sources for deforestation, planted soy area and cattle population. However, the data has some limitations and quality issues. The spatial extent of the study region did not capture all dynamics related to land use displacement at the Brazilian scale. Soybean expansion in Maranhão, Tocantins and Piauí might additionally lead to displacement processes linked to deforestation or the conversion of other ecosystems. While the temporal resolution of the analysis of yearly intervals captures the development of soybean expansion since it is an annual crop, it might not represent all dimensions of the multiannual life cycle of cattle. Moreover, model specification was limited due to the small number of observation. Even though these limitations challenged our findings, we provided new empirical insights into the spatial displacement process in the BR-163 region of the Brazilian Amazon.

Conclusion

Our findings suggest that the associations between cattle ranching, soy expansion and deforestation along the BR-163 have been affected by changes in land use policies and management following the implementation of the PPCDAm. While cattle ranching was closely associated with deforestation before the implementation of the PPCDAm, a temporal decoupling after 2004 was observed. Similarly, the transfer ratio of deforestation and soy expansion declined following the implementation of the PPCDAm.

Our empirical findings hence support earlier studies of land use displacement within the study region as identified by Arima et al. (2011) and Richards (2012) for the pre-PPCDAm period. However, the post-PPCDAm period was not equally affected by displacement. This underpins the importance of temporal discontinuity of the processes, as changes in policy affect these dynamics and are of major importance to take into account. However, we do not claim that displacement effects will not occur in future.

During the transition period following the implementation of the PPCDAm in 2004–2007, even though deforestation rates declined strongly, more land was deforested than used for cattle or soy production within the region. If deforestation dynamics stay decoupled from the displacement processes in MT, cattle ranching and soy production along the BR-163 will depend largely on the effort taken to promote sustainable intensification and actions to stop deforestation. However, we identified initial changes of agricultural expansion processes along with current efforts to decrease deforestation. Possible future pathways to achieve a persistent reduction of deforestation include subsidies for semi-intensive cattle pasture systems or taxes on conventional cattle pasture production, and the expansion of technology transfer and training services (Cohn et al., 2014; Strassburg et al., 2014).

Future studies on the process of intensification versus expansion of agricultural production could provide additional information on changes in land use management at the forest frontier after the implementation of the PPCDAm. Spatial displacement analysis will gain in considering temporal dynamics. For Brazil, it is additionally useful to analyze the full crop rotation system rather than a single crop type only, to accommodate for the ongoing intensification processes due to double cropping systems (Arvor et al., 2011a, 2011b). Plans to introduce palm oil plantation on a large scale in the Brazilian Amazon might move the displacement process to a new level, possibly displacing cattle production either further into the forest regions or to more distant places (Ramalho Filho, da Motta, de Freitas, Teixeira, 2010). The recent increase of deforestation rates in the Brazilian Amazon bring into question whether the current strategies against deforestation are sufficient to prevent future deforestation (INPE, 2014b).

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Appendix

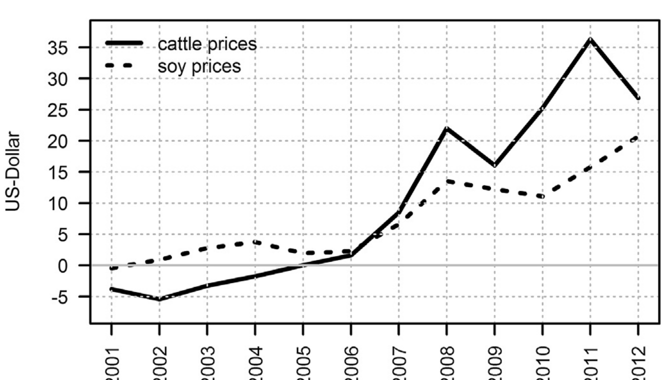

Fig. A1.

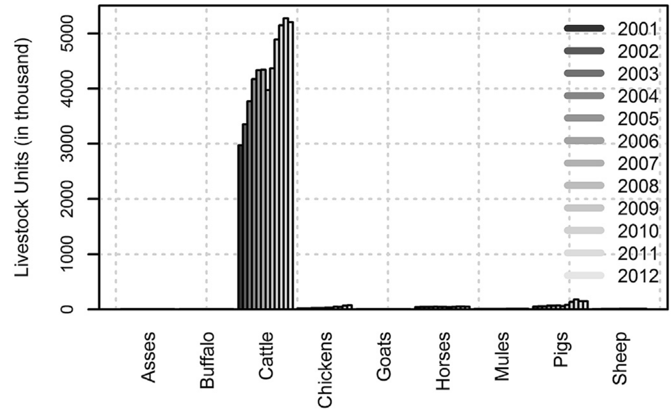

Fig. A2.

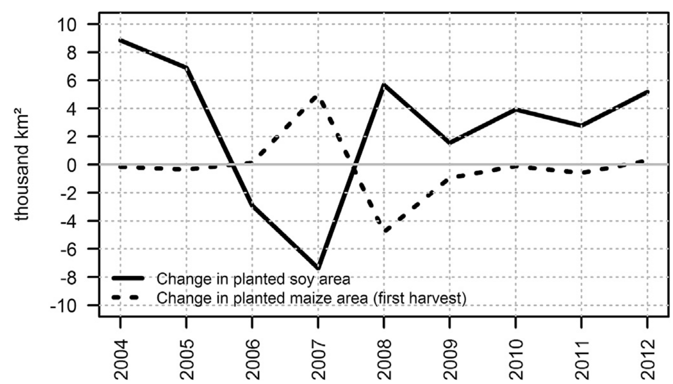

Fig. A3.

Table A1
Fixed effects panel regression including lagged soy expansion.

Model	Time period	Model specification	β
A1	2002–2004	$W_i\sum_{i=1}^{n}$Soy expansion Source$_{it}$	0.044475
		$W_i\sum_{i=1}^{n}$Soy expansion Source$_{i(t-1)}$	0.015465
		Adj. R^2	0.073
A2	2008–2012	$W_i\sum_{i=1}^{n}$Soy expansion Source$_{it}$	−0.119202***
		$W_i\sum_{i=1}^{n}$Soy expansion Source$_{i(t-1)}$	−0.060771**
		Adj. R^2	0.241

Model A1 & B1: Unbalanced Panel: $n = 21$, $T = 3$–4, $N = 74$.
Model A2 & B2: Unbalanced Panel: $n = 13$, $T = 3$–5, $N = 47$.
Significance levels: $p < 0.1$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

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